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Introductory to opto-mechanical engineering

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Synopsis of Technical Report

J.M. Sasian. "Design, assembly, and testing of an objective lens for a free-space photonic switching system", Optical Engineering 32(8), 1871-1878 (August 1993)

1. Introduction

In this paper, the design, lens tolerancing, assembly and testing of a lens with a high numerical aperture over a small field of view are discussed. Although this object lens is specifically designed for a free-space photonic switching system, the concepts in aberration corrections and the approaches to reach a high NA within small field of view are applicable in many applications such as microscope objective lens, laser scan lenses. It also serves as a nice guide for a lens designer to understand the whole process of making a lens system which is not only limited to lens design but included tolerancing, lens ordering, the strategy to maintain the budget, assembly and testing details, and the approximate time required for each task.

2. Summary of the synopsis

This synopsis mainly focuses on the general concepts in lens design of a fast objective lens with small field of view. It starts with a brief introduction on the lens requirement and lists the common aberration correction methods. Some explanations in aberration corrections are referenced from "Introduction to Lens Design with practical ZEMAX examples" by Joseph M Geary. Lens tolerancing, assembly and testing are included. Details in phonic switching system are neglected. Interested reader can refer the original paper for more details.

3. Lens requirement

Lens requirements	
Focal length:	15mm
Focal ratio:	1.5
Field of View:	7 degrees
Wavelength:	850 nm
Mapping:	F-sin(θ) $\pm 1.0\mu m$
Image surface:	Flat
Performance:	Strehl ratio> 0.95 over the full field
Telecentricity:	In the image space
Lenses:	Glass all spherical surfaces

4. Lens design

4.1 *General Considerations*

Starting point- Petzval portrait lens. Figure 1 shows the basic form and the aberration corrections are listed below.

- The abbe number in 2nd and 3rd lenses has to be different from one of the glasses used for 1st or 4th lens. This difference in abbe number helps to correct spherical aberration and coma as well as to flatten the tangential field.
- Spherical aberration is reduced by the doublet due to lens splitting.
- Two positive spaced lenses forming an objective allow the control of coma and astigmatism under a great diversity of conditions. The control is obtained using the relative lens power, the lens spacing, and the lens shapes.
- Expect field curvature, almost all the aberrations can be corrected.
- Field flattener lens are usually used new the image plane.
- Aberrations can almost be independently controlled and it has a great flexibility for locating the stop.

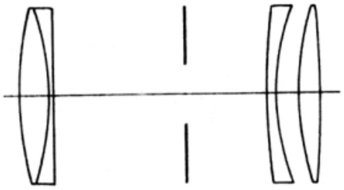


Figure 1 Basic form of Petzval portrait lens

4.2 Particular design

The lens design that is the subject of this paper is illustrated in Figure 2 and its specifications are given in Table 1.

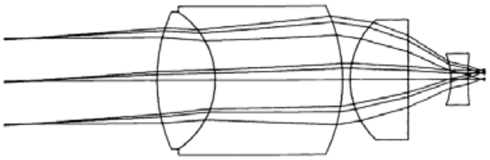


Figure 2. Cross section of the objective lens

Surface	Radius	Thickness	Glass
1 (stop)		15.5	AIR
2	21.086	6.835301	BK7
3	-10.090	13.03286	LASFN18
4	-21.086	0.9	AIR
5	+10.090	6.835301	BK7
6	Flat	5.038552	AIR
7	-8.17	2	BAK4
8	+33.012	1.548716	AIR

Table 1. Lens specification (in millimeters)

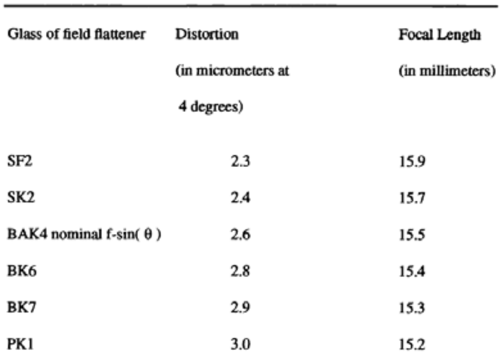
4.2.1 Aberration corrections

- Strong index break at the doublet to control spherical aberration.
- Flield flattener lens to control field curvature and distortion.

- Coma and astigmatism are corrected by the relative lens powers, thicknesses, and the spacing between the doublet and the positive lens.
- Distortion is this lens form can be controlled using the shape of the field flattener and was adjusted to provide the required f-sin(θ) mapping.
- The fining tuning of distortion is done by replacing the field flattener lens with different glass. Table 3 shows the variation of distortion and focal length as a function of glass type.

4.2.2 Performance

Figure 3 illustrates the progression of the wavefront deformation throughout the lens for the on-axis and 4 degrees off-axis positions.



Glass of field flattener	Distortion (in micrometers at 4 degrees)	Focal Length (in millimeters)
SF2	2.3	15.9
SK2	2.4	15.7
BAK4 nominal f-sin(θ)	2.6	15.5
BK6	2.8	15.4
BK7	2.9	15.3
PK1	3.0	15.2

Table 3 Variation of distortion and focal length

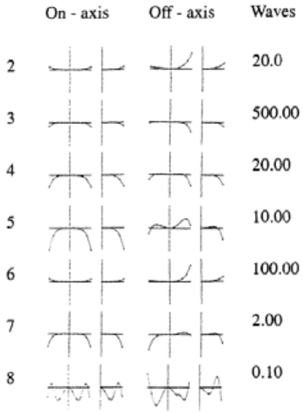


Figure 3 Progression of the wavefront deformation

The wavefront deformation within the entire field is below 0.1 waves and the Strehl is greater than 0.95. The Figure 3 provide us an insightful form understanding in a wavefront progression the cumulative at the field position 0.0 and 1.0. Large amounts of aberration are generated at the cemented interface and at the flat surface. The field flattener lens introduces a significant amount of coma and astigmatism, which are corrected by the doublet and the plano convex lens.

One noticeable point in this design is that the lens configuration involves only a flat surface, four different curvatures and two equal thicknesses. This greatly simplifies the lens fabrication and reduced the cost.

4.2.3 Alternate lens forms

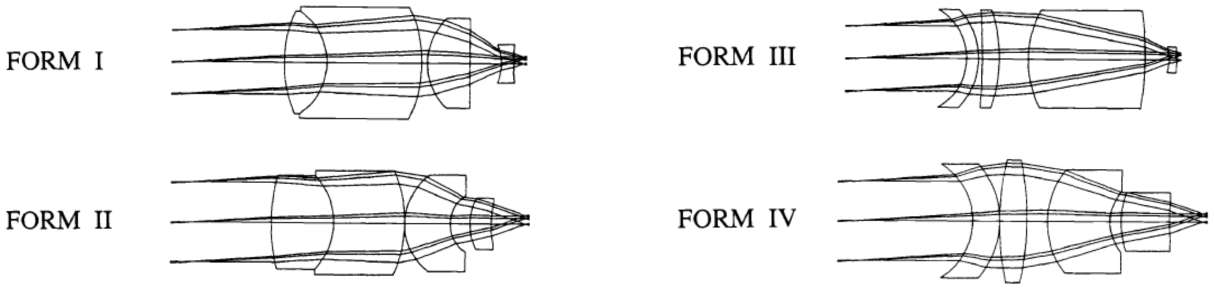


Figure 5. Four design forms of the Petzval type.

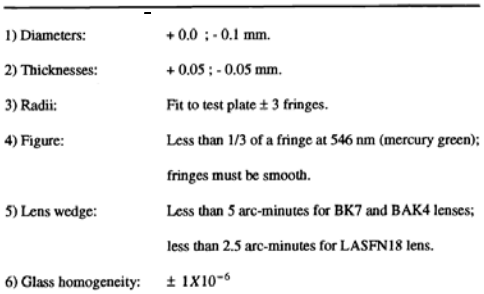
- Lens forms comprised of two parts: the two front lenses of each form compose the first part that contributes optical power and corrects spherical aberration.
- The two rear lenses compose the second part that corrects Petzval field curvature and distortion.
- The front and rear parts of lenses I and IV are interchanged to create forms II and III.

The reasons for the final decision on form I:

- The use of a doublet to simplify the lens barrel by decreasing by one of the elements to be mounted.
- The matched surface radii and thicknesses that simplify lens fabrication
- The flat surface of the 3rd element that simplifies the lens barrel and alignment
- The relatively long radii of all the surfaces ease the grinding and polishing operations.

5. Lens tolerancing

The author pointed out that the tolerancing study required a similar amount of time as the search-and-design task. Much effort was dedicated to achieve a high degree of confidence that the lens would work after specifying a set of tolerances. This required understanding in detail the behavior of the lens with perturbation. The tolerancing was performed manually and was approached by dividing the task into axial and tilt tolerance.



1) Diameters:	+ 0.0 ; - 0.1 mm.
2) Thicknesses:	+ 0.05 ; - 0.05 mm.
3) Radii:	Fit to test plate ± 3 fringes.
4) Figure:	Less than 1/3 of a fringe at 546 nm (mercury green); fringes must be smooth.
5) Lens wedge:	Less than 5 arc-minutes for BK7 and BAK4 lenses; less than 2.5 arc-minutes for LASFN18 lens.
6) Glass homogeneity:	$\pm\ 1X10^{-6}$

Table 4 Lens tolerances

- Axial tolerancing parameters: radii of curvature, thicknesses, indices of refraction and spacing. The change of the parameters maintains the axial symmetry of the lens.
- Departures of these parameters from nominal values introduce mainly spherical aberration and linear coma.
- The tilt tolerancing involved changes that alter the axial symmetry of the lens specifically tilt.
- Surface decenters were treated as surface tilts and thickness changes.
- The decentering and spacing of the third and fourth elements were used as compensators.
- The lens mounting must provide means to adjust the lens spacing and centering.
- Surface figure errors and glass inhomogeneity are excluded.
- It was decided to have 30 lens sets made and to allow the possibility of having some few objectives out of specification and the rest performing as needed.
- Two other aspects of the tolerancing were the doublet cementing and the lens performance as a function of the wavelength. The layer of cement between the first two lenses was modeled for different thicknesses 0 to 0.055mm and indices of refraction 1.51 to 1.85. The results was that the performance can be restored using the compensators.
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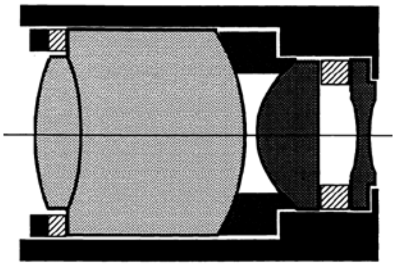
6. Lens Barrel

The lens housing illustrated in Fig. 6 consists of five parts: the barrel, two ring spacers, a plastic washer, and a threaded retaining ring.



- The lens barrel and the spacer rings are made from stainless steel stock.
- The first spacer has bevels on both inner edges to contribute to the lens alignment and to provide mechanical interfaces to the tangentially contacting convex surfaces.
- To simplify the lens alignment and the second lens spacer, the field-flattener lens was specified to be oversized and have flat annular surfaces.
- The inner diameters of the barrel were specified with a —0.0 + 0.025 mm tolerance, and some sets of spacers with different thicknesses were ordered to adjust the critical spacing between the pianoconvex lens and the field flattener.
- The typical wedge in these spacers is of the order of 1 arcmin.
- The plastic washer and the brass retaining ring hold all the components in position and complete the lens housing.

7. Lens Assembly and testing

A Twyman-Green interferometer with a diode laser source at 850 nm was arranged to interferometrically test the objectives. An iris was located at the proper distance to create the lens stop and a concave spherical mirror was used to reflect back the light focused by the objective to obtain a double-pass test configuration.

7.1 *Testing procedures*

- Spherical aberration was corrected by adjusting the thickness of the second lens spacer.
- The uniform (on-axis) coma was evaluated and corrected by rotating the doublet lens, the field flattener lens, or by exchanging any of these lenses.
- After on-axis testing is done, four field positions at 3.5 deg off-axis and at 0, 90, 180, and 270 deg around the field were evaluated.
- Any amount of linear coma observed was corrected by adjusting the thickness of the first spacer.
- Uniform astigmatism and linear astigmatism rarely were observed and when they were significant another lens combination was tried.
- The objectives were characterized using as a figure of merit the Strehl ratio of the worst field position of the five mentioned above.

7.2 *Focal length measurement*

An array of beams created by a diffraction grating of known period was focused onto a graticule. This graticule served to measure the spot position as imaged by another objective on a TV system. By knowing the grating period, the spot spacing, and the wavelength of illumination, we found the focal lengths.

8. Conclusion

This paper presented several details about the manufacturing of a lens which are rarely discussed in the literature. The completion of 27 objectives, including design, manufacturing, assembly, and testing, took approximately 1 yr. Essential to the success was the tolerancing analysis and the communication established with the manufacturer and, during the lens assembly, was the easy, quick, and user-friendly test setup.